

Discovering the World of Neutrinos

We humans are made of electrons and nucleons.

For every electron or nucleon, the universe contains $\sim 10^9$ neutrinos.

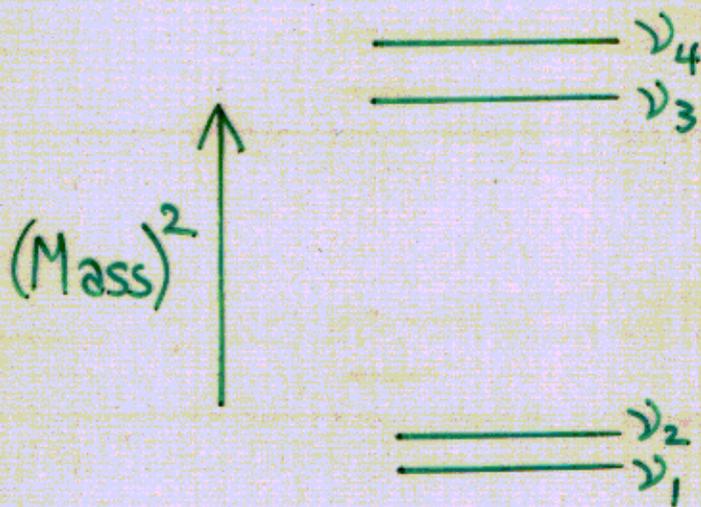
To understand the universe, we must understand neutrinos.

What have we learned?

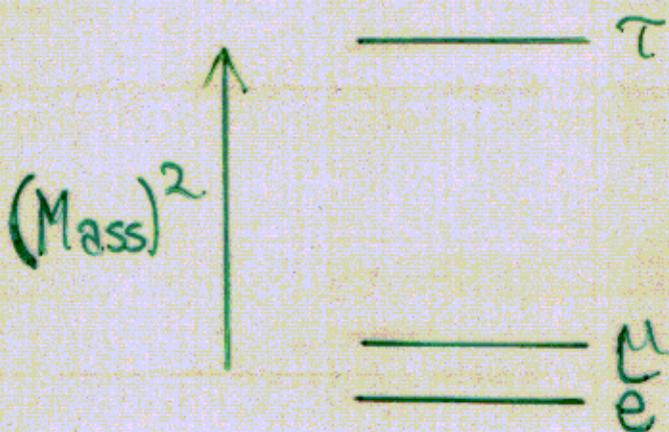
NEUTRINO PROPERTIES

Neutrinos almost certainly have masses and mix.

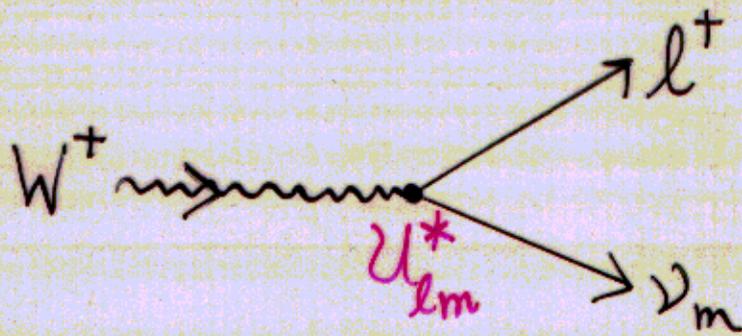
There is some spectrum of three or more neutrino mass eigenstates ν_m :



This is the neutrino analogue of the spectrum of charged-lepton mass eigenstates $l = e, \mu,$ and τ :



Mixing means that the weak interaction couples a given charged lepton of definite mass, l , to more than one neutrino of definite mass, ν_m .



U is the Maki-Nakagawa-Sakata leptonic mixing matrix. $U U^T = 1$.

The neutrino state produced in association with a specific charged lepton l is

$$|\nu_l\rangle = \sum_m U_{lm}^* |\nu_m\rangle$$

Neutrino of flavor l \uparrow \uparrow Neutrino of mass M_{ν_m}

If there are, say, four neutrino mass eigenstates, then one linear combination of them,

$$|\nu_{\text{sterile}}\rangle = \sum_m U_{sm}^* |\nu_m\rangle,$$

has no normal weak couplings.

The evidence for neutrino masses and mixing comes from the evidence for neutrino flavor oscillation.

Oscillation \Rightarrow Masses & Mixing

Oscillation cannot determine individual masses, but only the **splittings**

$$\Delta M_{mm'}^2 \equiv M_{\nu_m}^2 - M_{\nu_{m'}}^2.$$

Evidence for Oscillation

There are 3 pieces of evidence that neutrinos oscillate:

<u>Neutrinos</u>	<u>Evidence of Oscillation</u>	<u>Required ΔM^2 (eV²)</u>
Atmospheric	Compelling	3×10^{-3}
Solar	Strong	10^{-12} to 2×10^{-4}
LSND	Unconfirmed	0.2 to 6

If all 3 of these oscillations are genuine, then nature must contain —

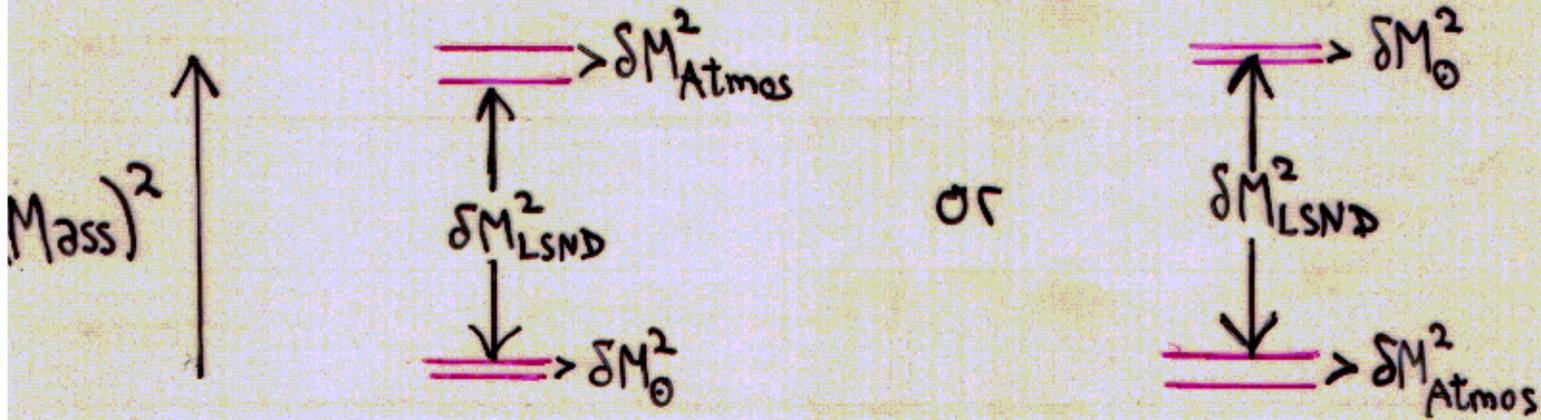
ν_e , ν_μ , ν_τ , ν_s (sterile)

↑ Does not enjoy weak interactions

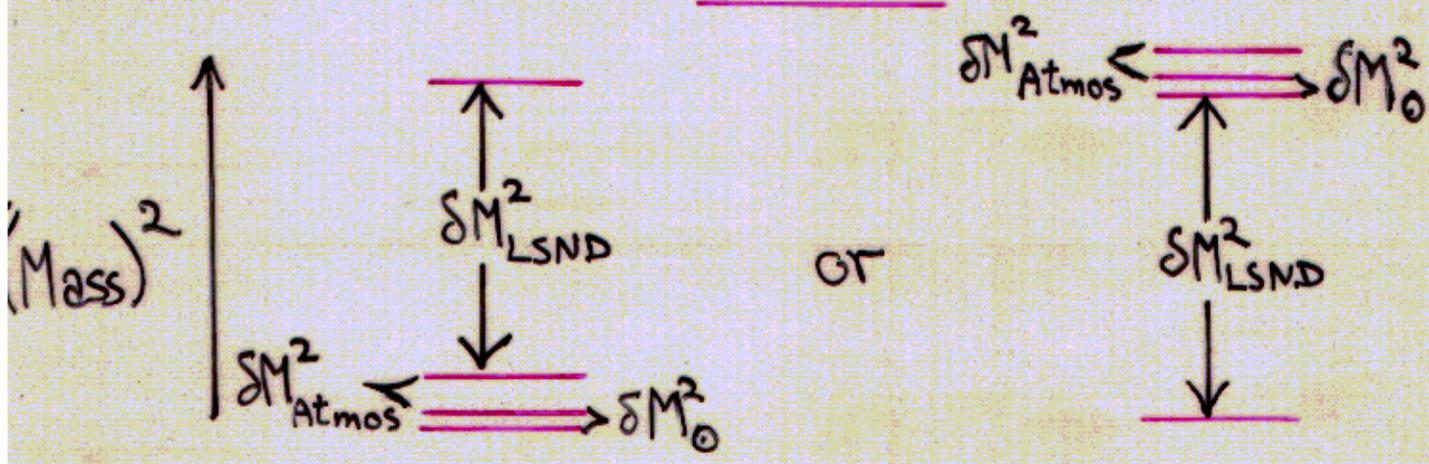
Possible 4-Neutrino (Mass)² Spectra

The spectrum can look like —

2+2



3+1



Flavor- l fraction of mass eigenstate ν_m
 $\equiv |\langle \nu_l | \nu_m \rangle|^2 = |U_{lm}|^2$

3+1

Neither atmospheric nor solar oscillation need produce ν_s .

Agreement with data not great.

(Barger et al.; Peres & Smirnov; Guinzi;
Foyle, Lisi, Marrone; Grimus & Schwetz)

2+2

Agreement with pre-2001 data good.

Either atmospheric or solar oscillation, or both, must produce ν_s with significant probability.

If

$$f_s^{\text{Atm}} \equiv \frac{P(\nu_\mu \rightarrow \nu_s)}{\sum_{l \neq \mu} P(\nu_\mu \rightarrow \nu_l)} \Big|_{\text{Atm}}, \quad f_s^{\odot} \equiv \frac{P(\nu_e \rightarrow \nu_s)}{\sum_{l \neq e} P(\nu_e \rightarrow \nu_l)} \Big|_{\odot}$$

then

$$f_s^{\text{Atm}} + f_s^{\odot} = 1$$

(Peres & Smirnov)

Sterile flavor cannot hide.

Atmospheric Neutrinos

The most compelling single piece of evidence that neutrinos oscillate is the Up/Down asymmetry of the atmospheric ν_μ flux.

Isotropy of the ≥ 2 GeV Cosmic Rays
+ Gauss' Law + No Oscillation

$$\Rightarrow \frac{\nu_\mu(\text{Up})}{\nu_\mu(\text{Down})} = 1$$

Super-K (amiokande)

$$\Rightarrow \frac{\nu_\mu(\text{Up})}{\nu_\mu(\text{Down})} = 0.54 \pm 0.04$$

$$\therefore \nu_\mu \longrightarrow \nu_?$$

Plyaskin: Without any oscillation,
at Super-K

$$\nu_{\mu} \text{ Flux Up} > \nu_{\mu} \text{ Flux Down.}$$

What is seen is —

$$\nu_{\mu} \text{ Flux Up} < \nu_{\mu} \text{ Flux Down.}$$

What Is ν_{τ} ?

Reactor data limit

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_{\mu}) \stackrel{\text{CPT}}{=} P(\nu_{\mu} \rightarrow \nu_e).$$

$\therefore \nu_{\tau} \neq \nu_e$ [Except maybe a little bit]

ν_{τ} could be —

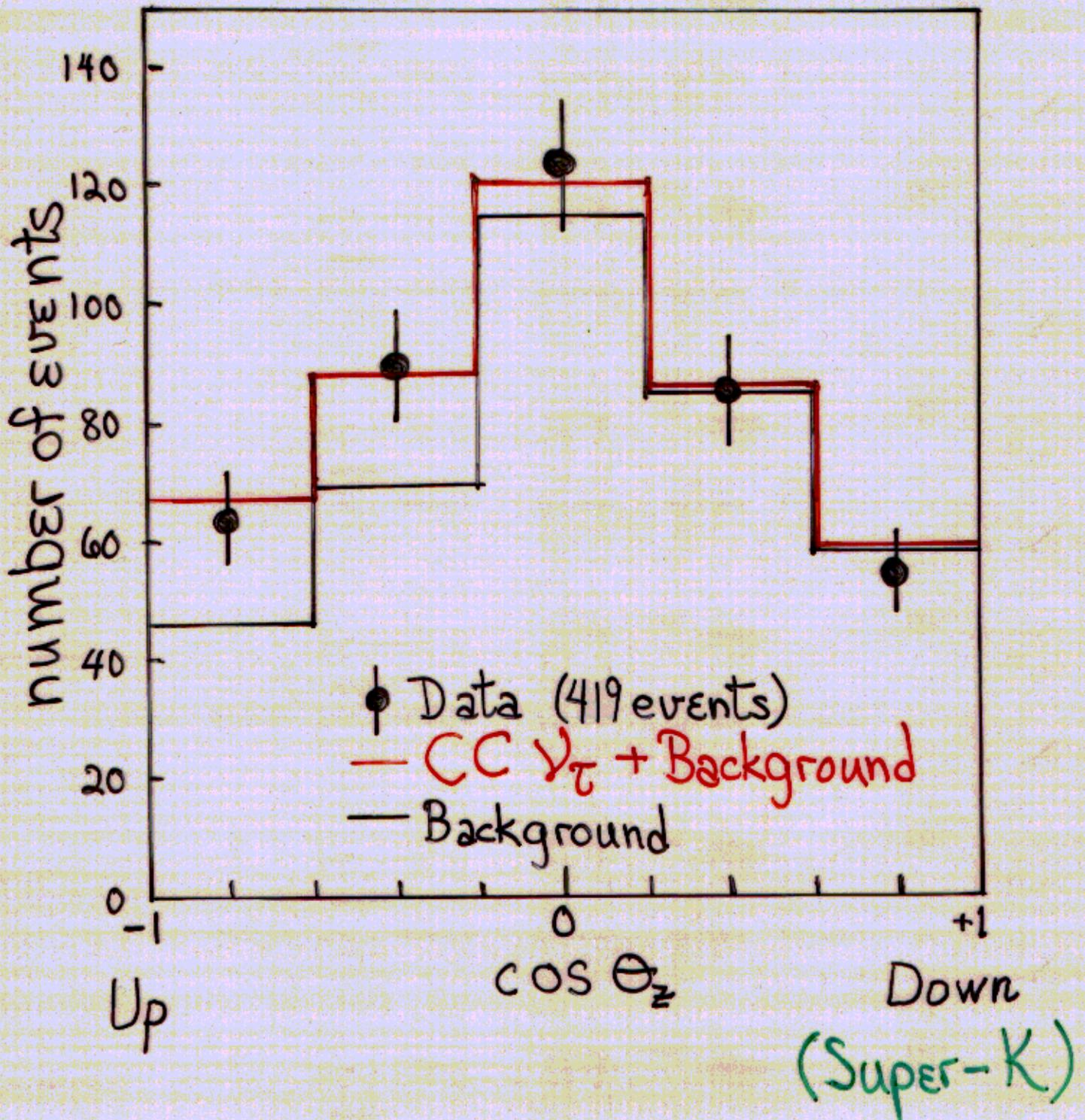
• ν_{τ}

• ν_s

• Sometimes ν_{τ} and sometimes ν_s .

Zenith angle distribution

τ -like events



From several pieces of evidence,

$$\nu_s \text{ fraction of } \nu_? \equiv f_s^{\text{Atm}} < 32\% \text{ at } 90\% \text{ CL} \\ (\text{Super-K})$$

Assuming $\nu_\mu \rightarrow \nu_\tau$ —

$$1.6 \times 10^{-3} < \Delta M_{\text{Atm}}^2 < 4 \times 10^{-3} \text{ eV}^2$$

$$\text{“} \sin^2 2\theta_{\text{Atm}} \text{”} (\nu_\mu - \nu_\tau \text{ Mixing}) > 0.88 . \\ (90\% \text{ CL, Super-K})$$

All quark mixing angles are small.
But at least one leptonic mixing angle
is \sim MAXIMAL.

Some Key Experiments

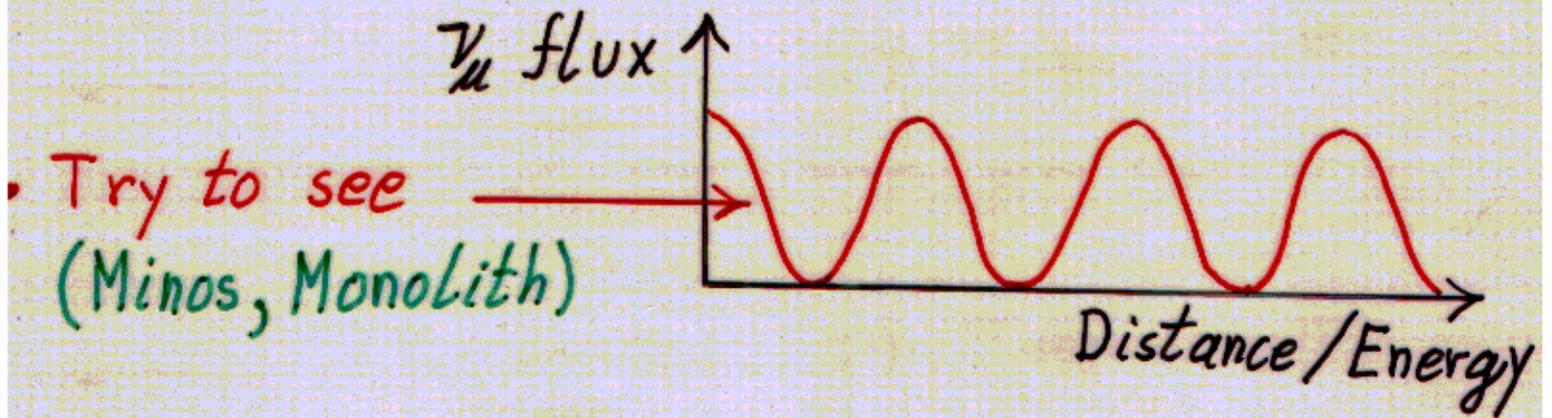
Test the $\nu_\mu \rightarrow \nu_\tau$ oscillation interpretation of the ν_{Atmos} data by seeking $\nu_\mu \rightarrow \nu_\tau$ in long-baseline accelerator-generated ν_μ beams.

K2K

Expected Events	No Oscillation	38
	Oscillation with ν_{Atmos} Parameters	27 (?)
Observed Events		28

Note: $38 - 2\sqrt{38} = 26$

In future -



- Try to verify that $\nu_{\tau} \cong \nu_{\mu}$ by observing ν_{τ} appearance more clearly (CERN to Gran Sasso)

Solar Neutrinos

The sun produces only ν_e .

Until now, ν_0 detectors have been sensitive largely, or exclusively, to ν_e .

Solar ν_e fluxes arriving at earth are .33 to .58 of the calculated fluxes produced in the solar core.

Hypothesis

Solar $\nu_e \rightarrow \nu_\mu, \nu_\tau, \text{ or } \nu_s$
via

M(ikheyev) S(mirnov) W(olfenstein)
effect in the sun

or

Vacuum oscillation between the sun and earth.

If $\nu_e \rightarrow \nu_{\mu, \tau}$, show us the $\nu_{\mu, \tau}$ flux arriving from the sun.

Sudbury Neutrino Observatory:

$$\text{Rate}(\nu_e + d \xrightarrow{cc} e^- + p + p) \Rightarrow \Phi_{\nu_e}$$

Super-Kamiokande:

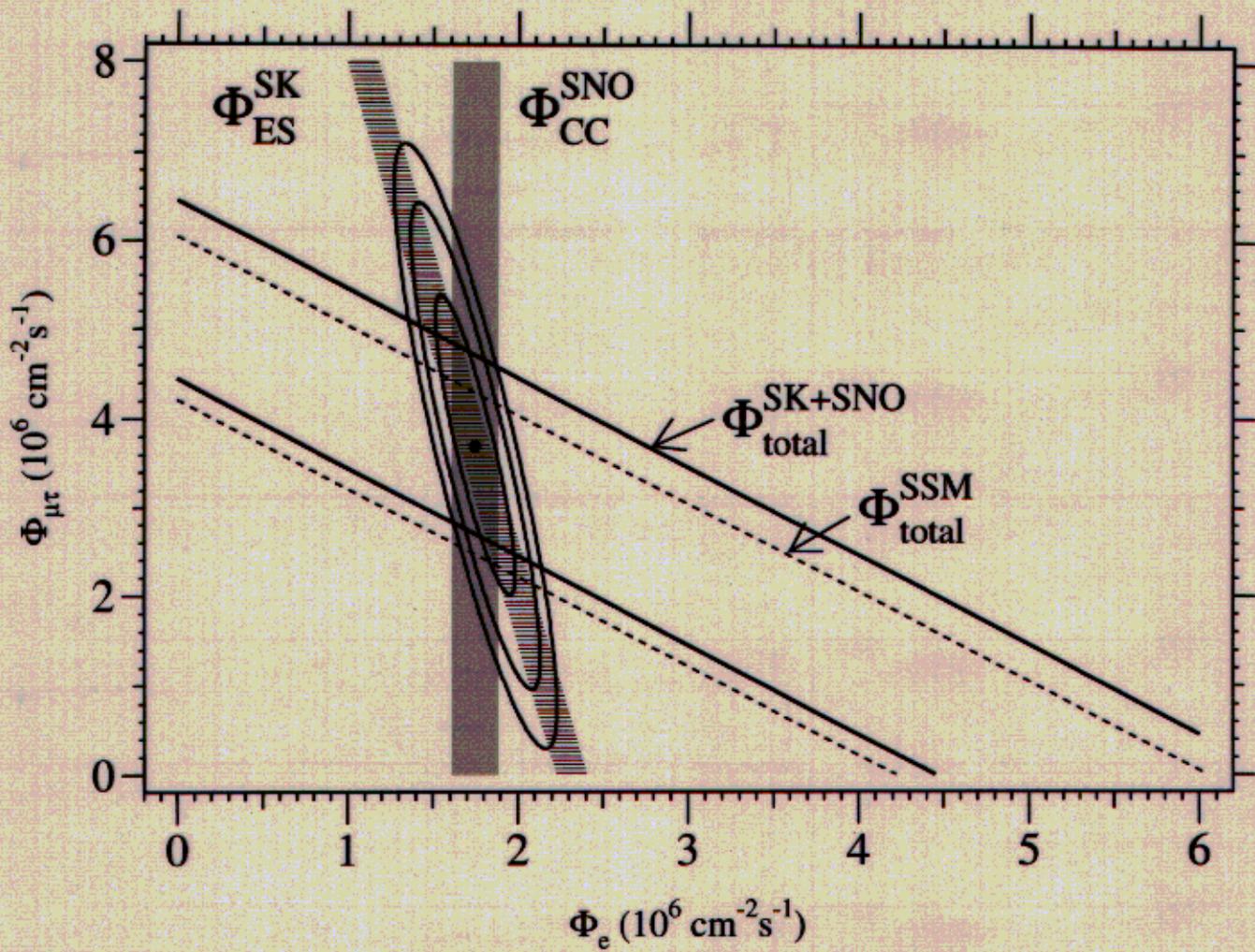
$$\text{Rate}(\nu_e e \xrightarrow{ES} \nu_e e) \Rightarrow \Phi_{\nu_e} + \frac{1}{6}(\Phi_{\nu_{\mu}} + \Phi_{\nu_{\tau}})$$

Together:

$$\Phi_{\nu_{\mu}} + \Phi_{\nu_{\tau}} = (3.69 \pm 1.13) \times 10^6 / \text{cm}^2 \text{ sec}$$

This is $> 3\sigma$ from zero.

[Fig.]



(SNO analysis)

2] If there is no $\nu_e \rightarrow \nu_s$, then

$$\underbrace{[\phi_{\nu_e} + (\phi_{\nu_\mu} + \phi_{\nu_\tau})]}_{\text{At earth}} = \underbrace{[\phi_{\text{total}}]}_{\text{Produced in solar core}}$$

$$(5.44 \pm 0.99) \times 10^6 / \text{cm}^2 \text{ sec}$$

[SNO + SK]

$$(5.05^{+1.01}_{-0.81}) \times 10^6 / \text{cm}^2 \text{ sec}$$

[Bahcall, Pinsonneault, Bas
"SSM" ^8B prediction]

Agreement is good.

How much room is left for $\nu_e \rightarrow \nu_s$?

ν_s fraction of non- ν_e solar flux $\equiv f_s^\odot$

$$= -0.12 \pm 0.62$$

[Snowmass-style quick and dirty calculation]

$f_s^\odot = 1.00$ is allowed.

[Bahcall, Gonzalez-Garcia, Peña-Garay]

$f_s^{\text{Atm}} + f_s^{\odot} = 1$ is certainly allowed.

==

spectra are completely alive.

==

LSND is alive.

Many versions of MSW or vacuum oscillation are still viable candidates for the explanation of the solar ν behavior.

(Bahcall, Gonzalez-Garcia, Peña-Garay)

$$10^{-12} < \delta M_{\odot}^2 < 2 \times 10^{-4} \text{ eV}^2$$

Mixing may be large or small.

Some key solar experiments

Confirm there is a $\nu_{\mu, \tau}$ component in the solar neutrino flux.

Continue to probe the dependence of the solar ν flux on—

Energy
Day or Night
Season

LSND

From $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance

$$0.2 < \Delta M_{\text{LSND}}^2 \lesssim 6 \text{ eV}^2$$

$$0.0009 \lesssim \sin^2 2\theta_{\text{LSND}} \lesssim 0.03$$

Key experiment

Confirm or disprove LSND: MiniBooNE

The future—What Would We Like to Learn?

- How many neutrino flavors, active and sterile, are there? Equivalently, how many neutrino mass eigenstates are there?
- What are the masses, M_{ν_m} , of the mass eigenstates, ν_m ?
- Are the neutrinos of definite mass—
 - * Majorana particles ($\bar{\nu}_m = \nu_m$),
 - or
 - * Dirac particles ($\bar{\nu}_m \neq \nu_m$)?
- How big are the elements $U_{\ell m}$ of the leptonic (MNS) mixing matrix?
Are there several big mixing angles?
Do the $U_{\ell m}$ contain ~~CP~~ phases?

- What are the electromagnetic properties of the neutrinos? What are their dipole moments?
- What are the lifetimes of the neutrinos? Into what do they decay?
- What are the implications of neutrino physics for the structure and evolution of the universe? Do CP phases in \mathcal{U} lead to our existence?
- What is the physics behind the masses, mixings, and other properties of neutrinos? How is it related to the physics behind the properties of quarks?

What Do We Already Know?
How Will We Learn More?

How Many Neutrinos Are There?

If MiniBooNE does NOT confirm LSND, then perhaps there are only ③.

If MiniBooNE DOES confirm LSND, so that ν_e , ν_{Atm} , and ν_{LSND} all oscillate, then there are at least —

3 active + 1 sterile.

Perhaps there are —

3 active + 3 sterile.

Perhaps there are —

3 active + ∞ sterile
Travel in
extra dimensions

Why do solar + atmospheric + LSND
oscillations $\Rightarrow \geq 4$ neutrinos?

With only 3 neutrino mass eigenstates,

$$\sum \delta M^2 = (M_{\nu_3}^2 - M_{\nu_2}^2) + (M_{\nu_2}^2 - M_{\nu_1}^2) + (M_{\nu_1}^2 - M_{\nu_3}^2) = 0$$

But —

Oscillating Neutrinos

Solar

Atmospheric

LSND

Required $|\delta M^2|$ (eV²)

10^{-12} to 10^{-4}

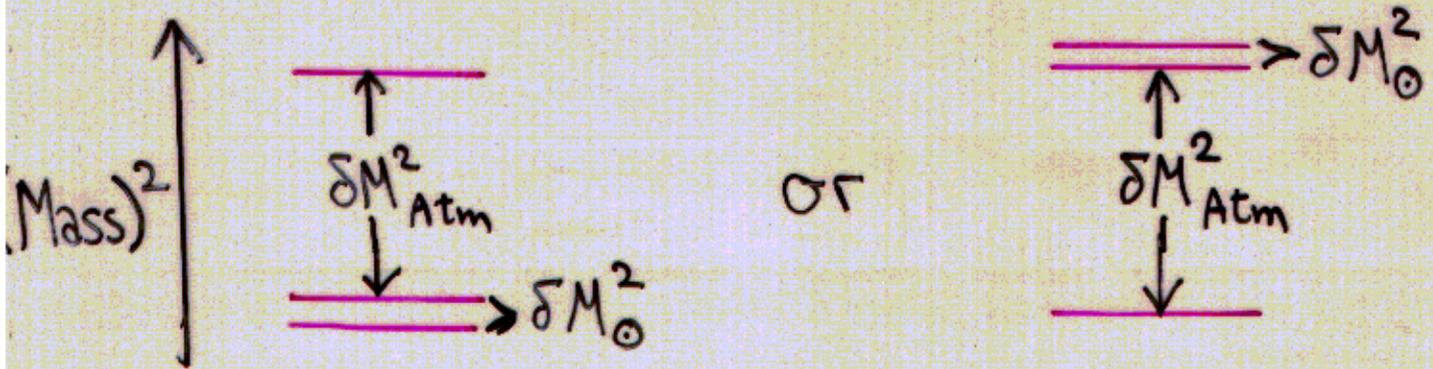
10^{-3}

1

$\sum \delta M^2 \neq 0$

How Much Do the Mass Eigenstates Weigh?

If only 3 neutrinos,



Which is it: Earth matter effects in Long Base Line experiments

How big is $\delta M_{\odot}^2 = 10^{-12} \text{ eV}^2$ to 10^{-4} eV^2 ?
Exactly how big is δM_{Atm}^2 ?

If 4 neutrinos —

10] Is it -

2 + 2

$$(f_s^{\text{Atm}} + f_s^{\circ} = 1)$$

or

3 + 1

$$(\text{Can have } f_s^{\text{Atm}} + f_s^{\circ} \ll 1) ?$$

If 2+2 -

Is the pair on top the atmospheric pair,
or the solar pair ???

From oscillations we learn only
(Mass)² splittings.

Where is the ZERO of (Mass)² ?

Possibilities

The neutrinos may be heavier than required by their splittings.

Suppose they are not!

If the LSND oscillation is genuine, there are one or more neutrinos ν_m with masses M_{ν_m} obeying

$$M_{\nu_m} \geq \sqrt{\delta M_{\text{LSND}}^2} \gtrsim \sqrt{0.2 \text{ eV}^2} \approx 0.4 \text{ eV}.$$

$$\sum_{\text{Heavies}} \text{BR}({}^3\text{H} \rightarrow {}^3\text{He} + e^- + \nu_m) \sim \sum_{\text{Heavies}} |U_{em}|^2$$

$$= \begin{cases} \sim 1 & ; \\ \text{Small} & ; \end{cases} \begin{array}{l} \text{---} \circ \\ \text{---} \text{Atm} \\ \text{---} \text{Atm} \\ \text{---} \circ \end{array} \begin{array}{l} \sigma \\ \sigma \end{array} \begin{array}{l} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array}$$

20 A tritium experiment sensitive to $M_{\nu_m} \lesssim 0.4 \text{ eV}$ could prove very fruitful. (Karlsruhe, Mainz, et al.)

If the LSND oscillation is not genuine, the heaviest mass eigenstate need be no heavier than

$$\sqrt{\Delta M_{\text{Atm}}^2} \sim \sqrt{3 \times 10^{-3} \text{ eV}^2} \sim 0.05 \text{ eV.}$$

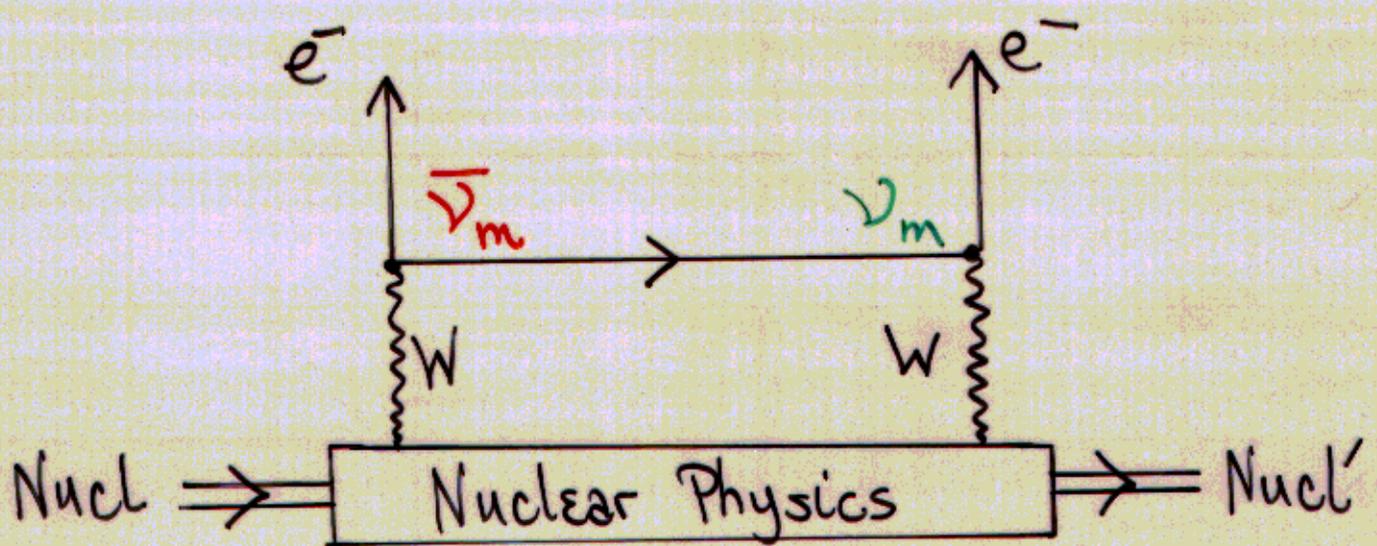
That is beyond the current plans for tritium.

Is there a much more sensitive probe of absolute masses??

Does $\bar{\nu}_m = \nu_m$?

The only approach being pursued so far is the search for

$0\nu\beta\beta$ decay.



This reaction will occur iff $\bar{\nu}_m = \nu_m$.

A number of experiments are proposed.

A Bonus From $0\nu\beta\beta$

A measured Rate ($0\nu\beta\beta$) and a calculated Nuclear Matrix Element would determine —

$$M_{\beta\beta} = \sum_m M_{\nu_m} U_{em}^2.$$

$M_{\beta\beta}$ is a different linear combination of ν masses than those measured in ν oscillation

$M_{\beta\beta}$ could test mass spectra suggested by oscillation.

(Barger, Bilenky, Farzan, Giunti, Grimus, B.K.,
Klapdor-Kleingrothaus, Päs, Pascoli, Petcov,
Smirnov, Whisnant)

13 What Are the Mixing Matrix Elements $U_{\ell m}$? 21

With L = distance a neutrino travels,
and E = neutrino energy,

the oscillation probability is

$$P(\vec{\nu}_\ell \rightarrow \vec{\nu}_{\ell'}) =$$

$$= \delta_{\ell\ell'} - 4 \sum_{m>m'} \text{Re}(U_{\ell m}^* U_{\ell' m} U_{\ell m'} U_{\ell' m'}^*) \sin^2(\delta M_{mm'}^2 \frac{L}{4E})$$

$$\pm 2 \sum_{m>m'} \text{Im}(U_{\ell m}^* U_{\ell' m} U_{\ell m'} U_{\ell' m'}^*) \sin(\delta M_{mm'}^2 \frac{L}{2E})$$

Complex phases in U can lead to \mathcal{CP} .

The \mathcal{CP} asymmetry

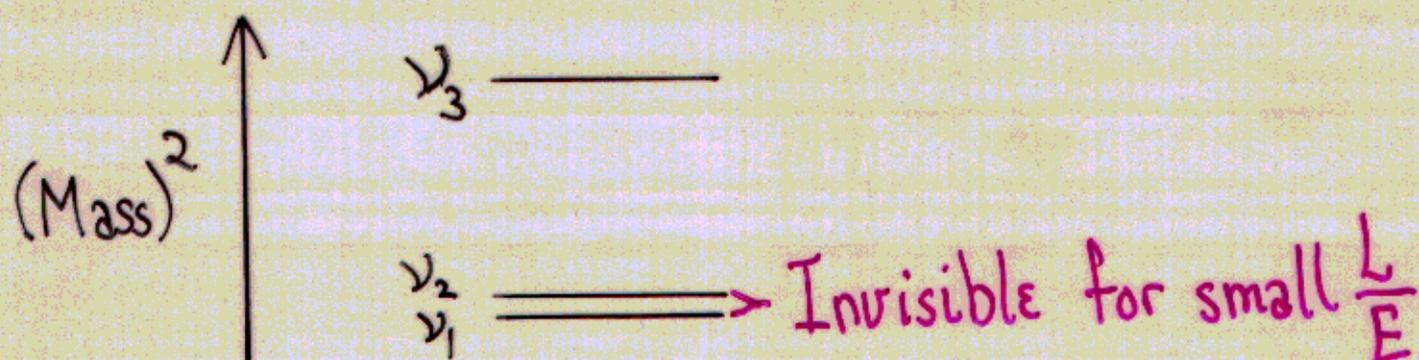
$$\Delta_{\mathcal{CP}}(\ell\ell') \equiv P(\nu_\ell \rightarrow \nu_{\ell'}) - P(\bar{\nu}_\ell \rightarrow \bar{\nu}_{\ell'})$$

could lead to a lepton asymmetry
 $\#(\ell^+) \neq \#(\ell^-)$ in the early universe.

To this why we are here??

23

Sizes $|U_{\ell m}|$ can be determined from oscillations in which the spectrum looks like just 2 neutrinos.



The $\nu_2 - \nu_1$ pair looks like 1 neutrino.

Leptons vs. Quarks

The quark and lepton mixing matrices can each be parametrized in terms of mixing angles and \mathcal{CP} phases.

14 All quark mixing angles are small.

At least one lepton mixing angle, governing ν_{Atm} oscillation, is BIG.

Maybe a second one, governing ν_{e} oscillation, is also BIG.

At least one lepton mixing matrix element is small:

$$|U_{e3}|^2 \lesssim 0.03.$$

(CHOOZ, Palo Verde)

A challenge to measure.

Is the quark-lepton difference a clue to the physics behind masses?

5
The Flavor Physics Working Group (P2)
will discuss the physics of both quark
and lepton flavor, and possible relations.

Possible \mathcal{CP} Phases in \mathcal{U}

Number of Neutrinos	Universal	Majorana (Only if $\bar{\nu}_m = \nu_m$)
2	0	1
3	1	2
4	3	3

Why extra phases when $\bar{\nu}_m = \nu_m$?

Because then

$$\text{Charge conjugate}(\nu_m) \equiv \gamma_2 \nu_m^* = \nu_m,$$

so phases cannot be removed from \mathcal{U} by phase-redefining ν_m .

CP Phases	Affect ν Oscillation	Affect $\beta\beta\omega$
Universal	Yes	No
Majorana	No	Yes

If there are only 3 neutrinos, then, with $P(\nu_e \rightarrow \nu_{e'}) - P(\bar{\nu}_e \rightarrow \bar{\nu}_{e'}) \equiv \Delta_{CP}(ll')$,

$$\Delta_{CP}(e\mu) = \Delta_{CP}(\mu\tau) = \Delta_{CP}(\tau e) \\ = 16 J S_{12} S_{23} S_{31},$$

where

$$J \equiv \text{Im}(U_{e1} U_{e2}^* U_{\mu 1}^* U_{\mu 2}),$$

and

$$S_{mm'} \equiv \sin \left[1.27 \delta M_{mm'}^2 (\text{eV}^2) \frac{L (\text{km})}{E (\text{GeV})} \right].$$

Life is simple, but hard.

In B decays we expect different CP asymmetries in different decay modes.
Life is rich but hard

26 Authors who have discussed \mathcal{CP} :

Arafune & Sato; Bernabeu; Dick, Freund,
Lindner, Romanino; Fisher, B.K., McFarland;
Gago, Pleitez, Funchal; Schubert;
Parke & Weiler; Gonzalez-Garcia, Grossman,
Gusso, Nir; Many Others

\mathcal{CP} in neutrino oscillation can hopefully
be studied in $\sim 10^3$ km Base Line
future experiments.

Summary

There is a rich world of flavor physics in the neutrino sector.

It awaits our exploration.

Coming experiments on CP or rare B , D , and K decays stand to reveal a rich new world in the quark sector.

In flavor physics, there is a lot that we would like to help make happen.
